This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 681647).

A monitored neutrino beam at CERN: perspectives for high-precision neutrino cross-section measurements with ProtoDUNE

F. Terranova(*) on behalf of the ENUBET Collaboration

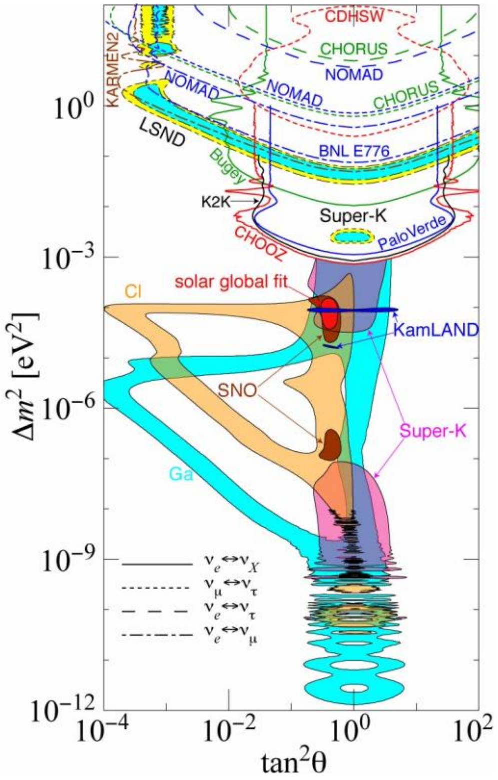
(*) University of Milano-Bicocca & INFN Milano-Bicocca

The irresistible rise of accelerator neutrino beams

Neutrinos have always been “embarrassing” for the Standard Model (which, has been originally conceived with massless neutrinos to wipe off such an embarrassment ☺)

- Their masses are incredibly small (<30 meV !) and we don’t know yet neither the reason for it nor the exact value of these masses
- Their mixing is completely different than quarks and we don’t know why
- They might violate CP but, unlike quarks, CP violation in neutrinos could play a leading role to explain matter-antimatter unbalance in the universe (leptogenesis)
- We do not even know if they are Dirac or Majorana fermions because they are the only neutral elementary fermions we are aware of

The discovery of neutrino oscillations in **1998 (Nobel Prize)** provided us with a terrific tool to establish that neutrino were massive particles. The discovery of a “large” size of the ϑ_{13} angle in **2012 (Breakthrough Prize)** demonstrated that <u>accelerator neutrino beams can measure all the free parameter of the Standard Model for neutrinos, except one</u> (the mass of the lightest mass eigenstates)

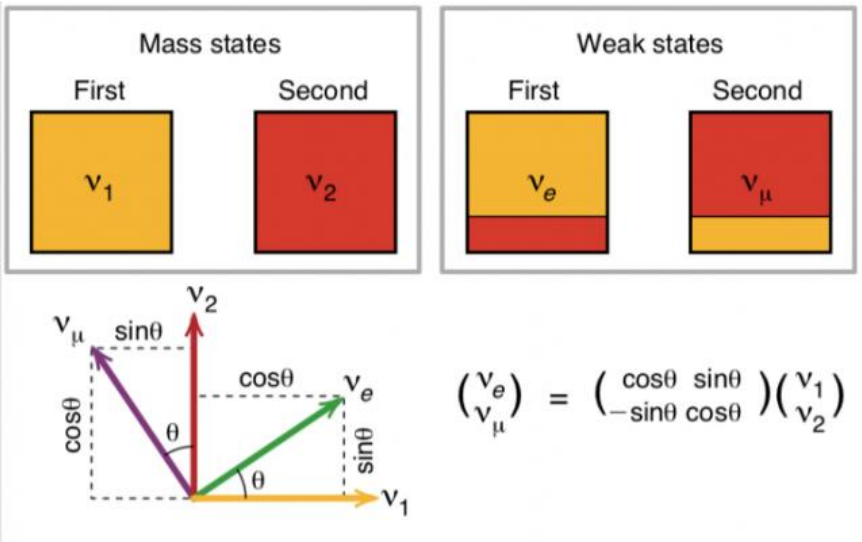


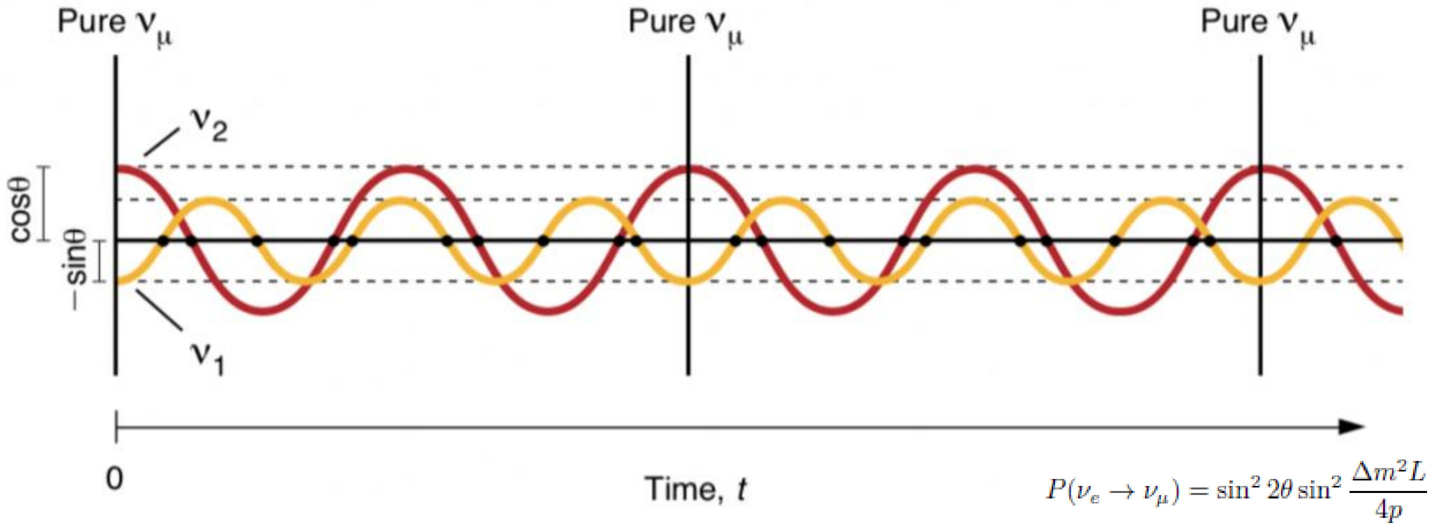
Mixing parameters in 1997…

$$|U| = \begin{bmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu1}| & |U_{\mu2}| & |U_{\mu3}| \\ |U_{\tau1}| & |U_{\tau2}| & |U_{\tau3}| \end{bmatrix} = \begin{bmatrix} 0.801 \ldots 0.845 & 0.513 \ldots 0.579 & 0.143 \ldots 0.156 \\ 0.232 \ldots 0.507 & 0.459 \ldots 0.694 & 0.629 \ldots 0.779 \\ 0.260 \ldots 0.526 & 0.470 \ldots 0.702 & 0.609 \ldots 0.763 \end{bmatrix}$$

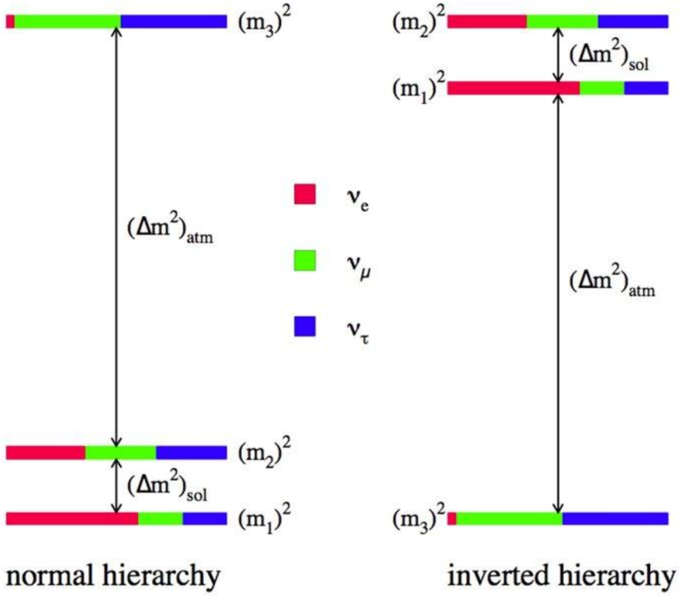
… and in 2021

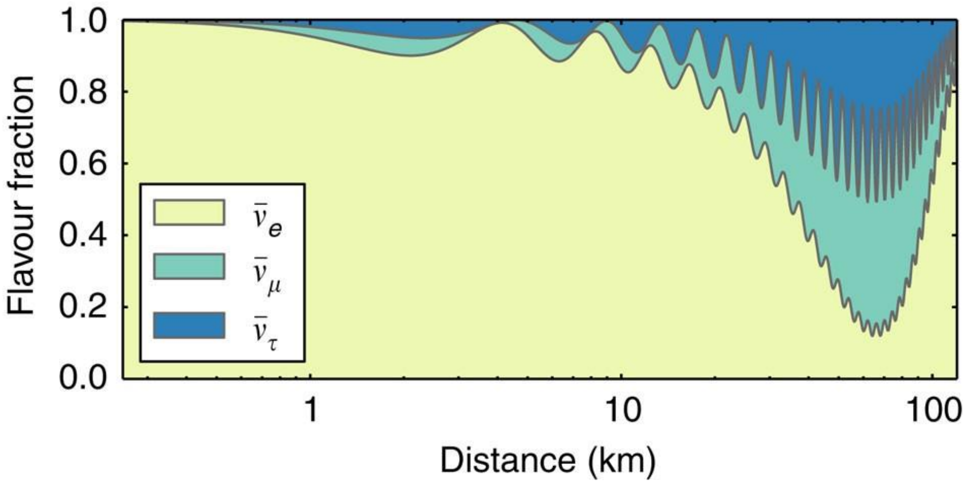
70 years of research in one sentence: neutrinos come in three different flavors, which are eigenstates of the weak interaction lagrangian. But each flavor is a linear superposition of three different mass eigengenstates (*).





$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4p}$$
$$\simeq \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}.$$





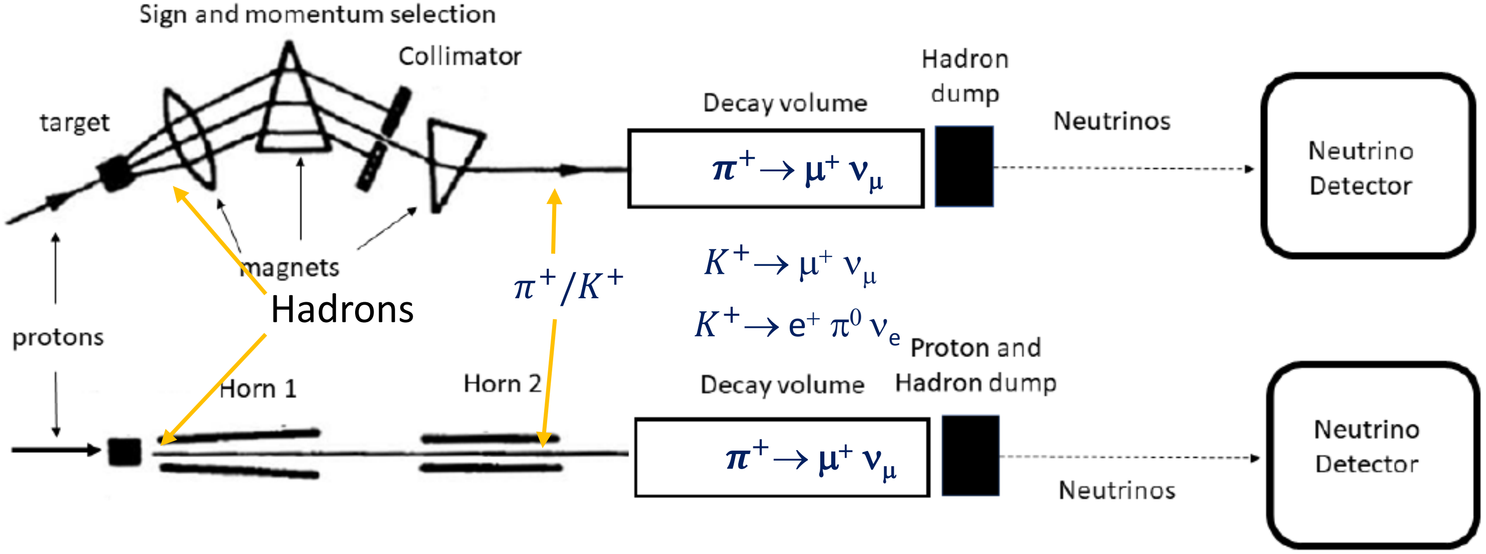
$$P_{\nu_\alpha \to \nu_\beta}(t) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2$$
$$= \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$
$$+ 2 \sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin\left(\frac{\Delta m^2_{ij} L}{4E}\right),$$

where $\Delta m^2_{ij} = m^2_i - m^2_j$ and we can rewrite:

$$\frac{\Delta m^2_{ij} L}{4E} \approx 1.267 \frac{\Delta m^2_{ij}[eV^2] \times L[km]}{E[GeV]}.$$

(*) See any particle physics book written after 2012. For the sake of advertising ☺ :
F. Terranova , «A modern primer in particle and nuclear physics», Oxford Univ. Press, 2021

Best-in-class: accelerator neutrino beams



«narrow band beam»
(lower flux higher precision)

«wide band beam»
(higher flux lower precision)
Like T2K, NOvA, DUNE, HyperK...

$$P_{\nu_e \to \nu_\mu} \simeq \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2}$$
$$+ \alpha \sin 2\theta_{13}\, \xi \sin\delta \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$
$$+ \alpha \sin 2\theta_{13}\, \xi \cos\delta \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$
$$+ \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}.$$

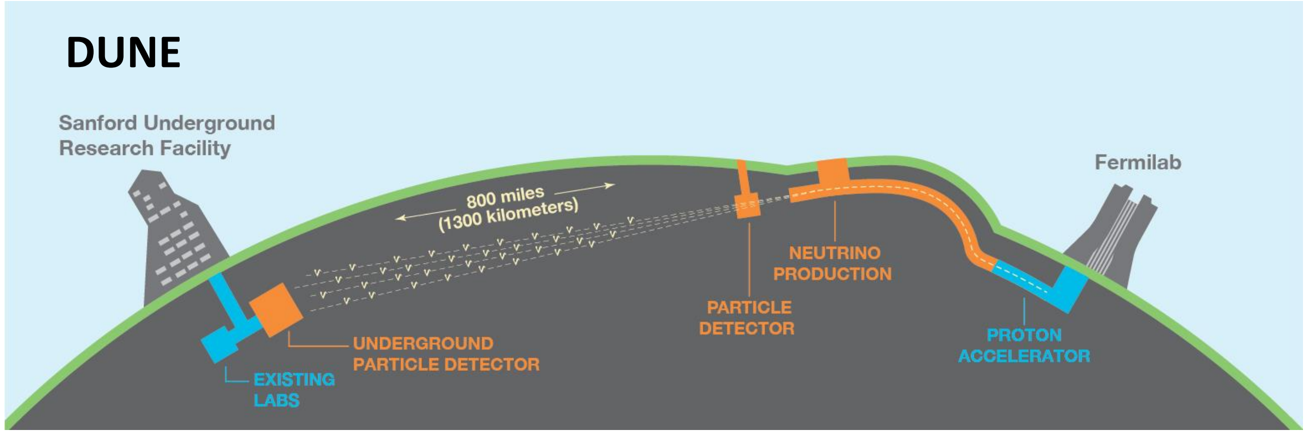
$\Delta \equiv \Delta m^2_{31} L/(4E)$ — Year 2005 → «**oscillation phase**» It is O(1) for E= O(1 GeV) and L= O(100 km) Cool, we can build experiment on Earth ☺

$\alpha \equiv \Delta m^2_{21}/|\Delta m^2_{31}|$ — Year 2003 → Must be <1. The larger the better. We know now that is 0.28

$\xi \equiv \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$

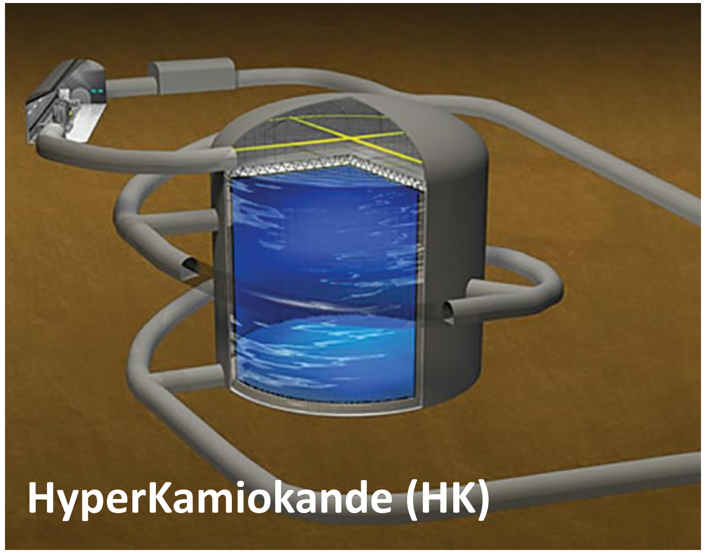
$\sin^2 2\theta_{13}$ — Year 2012 → The larger the better! It is O(1) in neutrinos! (it is tiny in quarks..)

The physics case is strong: Let’s do it!

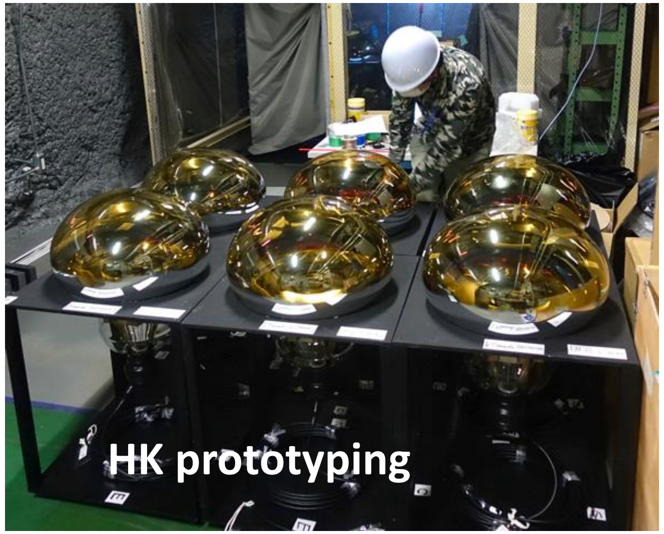



DUNE site excavation


DUNE prototyping


HyperKamiokande (HK)


HK site excavation


HK prototyping

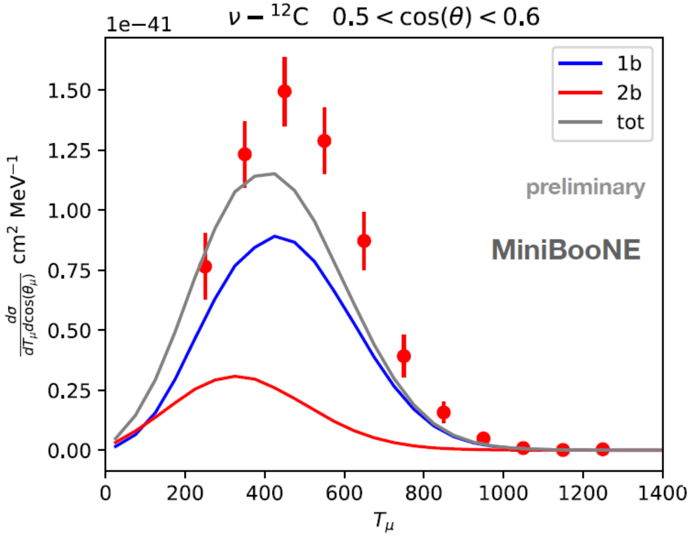
A harmful ignorance: cross-sections

- Major impact on the sensitivity of DUNE and HyperKamiokande (already dominant in T2K…)

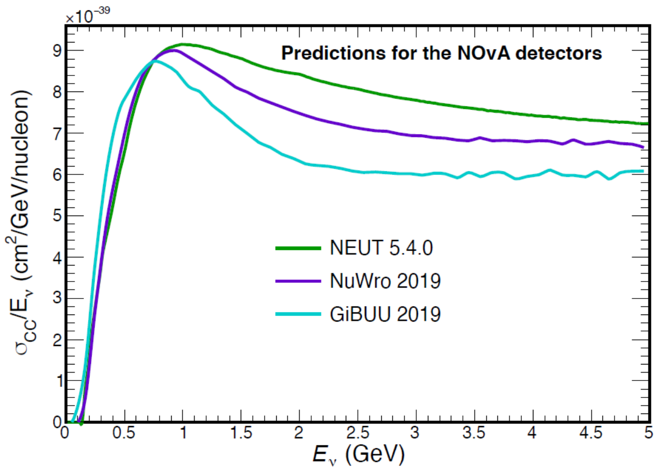
T2K

	Systematic uncertainties		
Beam mode	Neutrino		
SK sample	1 Ring μ-like	1 Ring e-like	1 Ring e-like 1de
Flux	5.1%	4.8%	4.9%
Cross-section	10.1%	10.3%	12.0%
SK	2.9%	4.4%	13.4%

- Modeling of nuclear effects in neutrino interactions

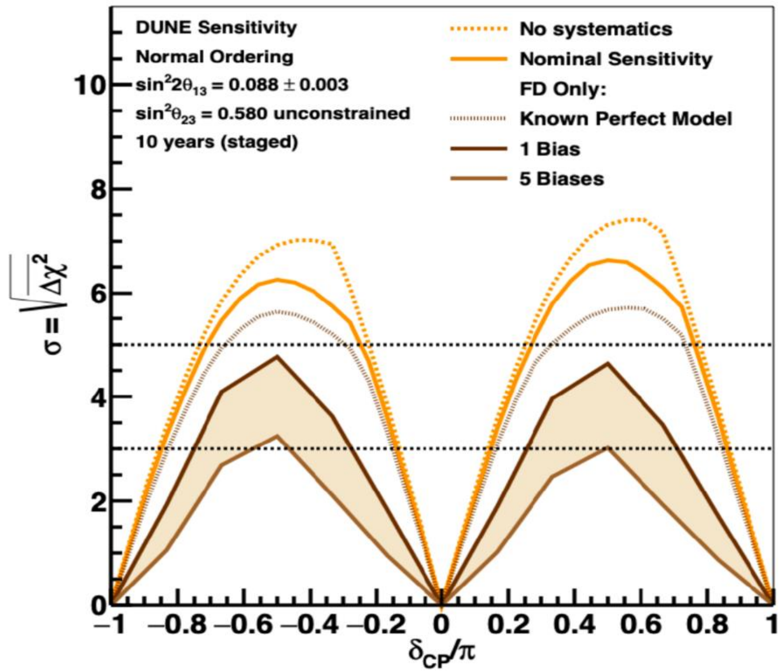


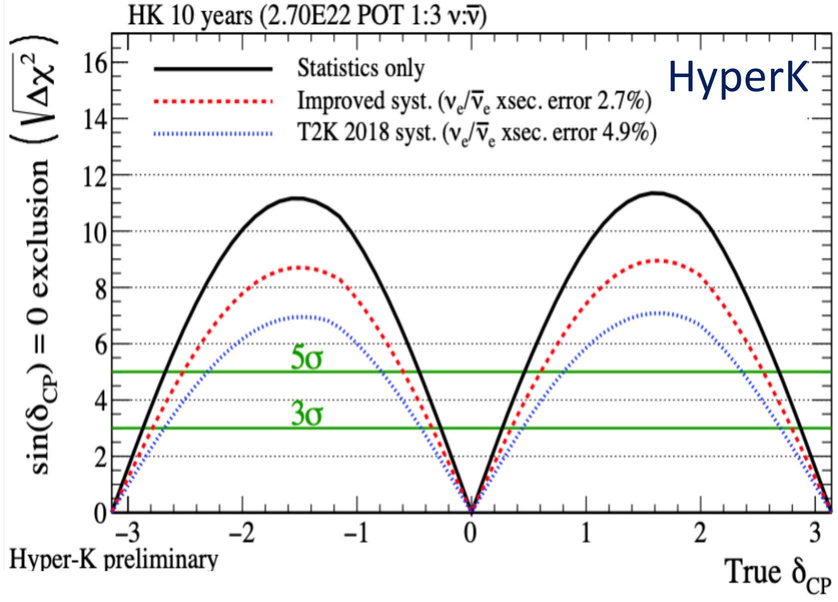
N. Rocco, Nufact2022



J. Paley, Nufact2022

DUNE





For a review see e.g. NuSTEC white paper, arXiv:1706.03621

The rationale of ENUBET

The knowledge of neutrino cross section is stuck at 10-30 % level and the needs of the neutrino community are at 1% level because:

- Leading systematics for long baseline experiments → Neutrino Oscillation Physics
- Limited possibility to validate nuclear electroweak effects ("nucleus and nuclear correction") → Electroweak physics
- Neutrino generators based on different approach still provide results with >50% discrepancies → Nuclear Physics

From the **European Strategy for Particle Physics Deliberation document**:

To extract the most physics fromDUNE and Hyper-Kamiokande, a complementary programme of experimentation to determine neutrino cross-sections and fluxes is required. Several experiments aimed at determining neutrino fluxes exist worldwide. The possible implementation and impact of a facility to measure neutrino cross-sections at the percent level should continue to be studied.

From the Physics Briefbook for the **European Strategy for Particle Physics (arXiv:1910.11775)**

Both nSTORM and ENUBET are to a large extent site-independent concepts, studies and R&D; however both consider a possible implementation at CERN. For nSTORM, under the auspices of the PBC program, an initial study of implementation at CERN was carried out, and no showstoppers have been identified. For ENUBET the option of using SPS as the proton driver has been considered in greater detail with a possible site in the North Area and the ProtoDUNEs as neutrino detectors.
A dedicated study should be set-up to evaluate the possible implementation, performance and impact of a percent-level electron and muon neutrino cross-section measurement facility (based on e.g. ENUBET or nSTORM) with conclusion in a few years time.

What is needed for a new generation cross-section facility?

- Measure the neutrino flux of a xsect-dedicated short baseline beam with a precision <1% in ν_e and ν_μ. **Flux** is the dominant systematics. Generally known at 10% level with a few notable exceptions
  - Combine hadroproduction data + ν-e scattering (5-10%). World record: arXiv:2209.05540 (3.3-4.7% !)
  - Monitored neutrino beam (this talk) 0.5-1 %
  - Muon storage ring (nuSTORM) <1%
- Measure the **energy** of the neutrino without relying on the final state to get rid of all biases coming from nuclear reinteractions
  - Narrow band beams combined with movable detectors (rough approximation of a "monocromatic beam")
  - Monitored neutrino beam "Narrow band- off-axis technique" (this talk)
- Use the same **target** ad DUNE and HyperK + low Z target (existing or new experiments)
  - Some information available from near detectors (but, then, issues with flux × cross-section deconvolution)
  - New experiments with existing or novel detectors along a short-baseline beam (following the success of dedicated experiments like Minerva)
- **Statistics** (double differential cross sections)
  - Not an issue for ν_μ. O(10^4) ν_e in conventional beams and monitored neutrino beams
  - O(10^6) in all flavors using muon storage rings (nuSTORM)

For a review see e.g. A. Branca et al., Symmetry 13 (2021) 9, 1625

ENUBET: the first monitored neutrino beams

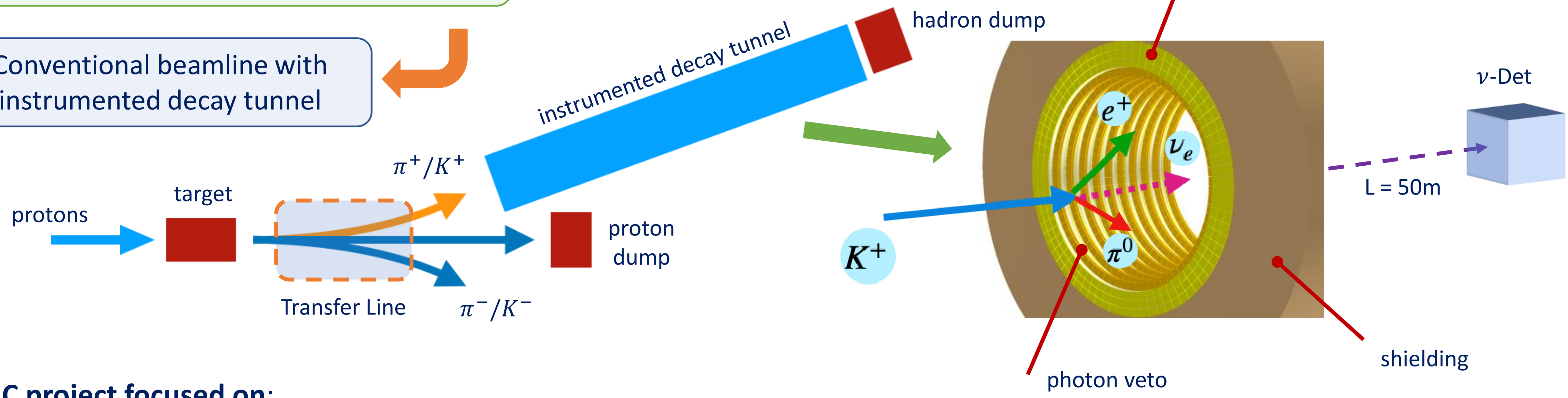
How do we achieve such a precision on the neutrino cross-section, flavor composition and energy?

Monitored ν flux from narrow-band beam

measure rate of leptons $\Leftrightarrow$ monitor ν flux

Conventional beamline with instrumented decay tunnel

A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155



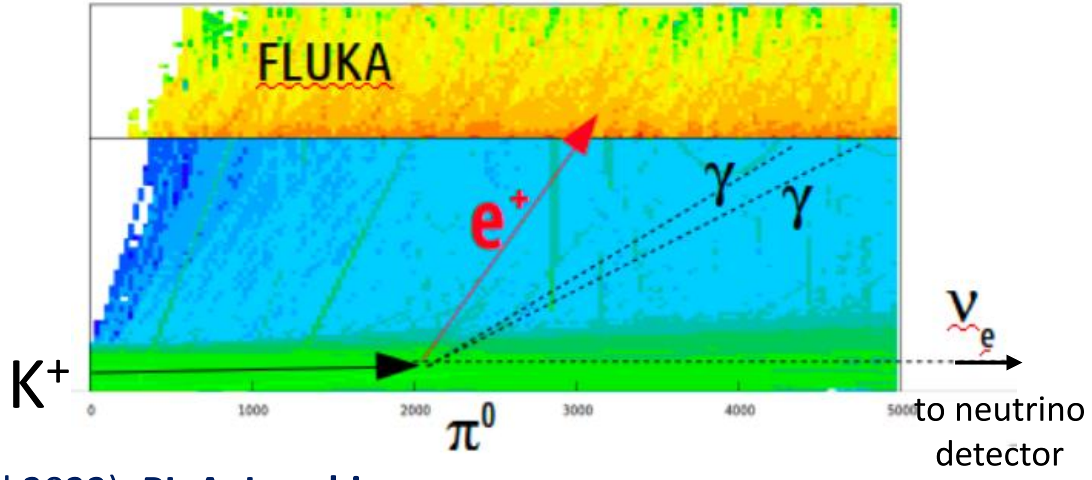
- **ERC project focused on**: measure positrons (instrumented decay tunnel) from K_{e3} $\Longrightarrow$ determination of ν_e flux;
- **As CERN NP06 project**: extend measure to muons (instrumented decay tunnel) from $K_{\mu\nu}$ and (replacing hadron dump with range meter) $\pi_{\mu\nu}$ $\Longrightarrow$ determination of ν_μ flux;

Main systematics contributions are bypassed: hadron production, beamline geometry & focusing, POT;

What is ENUBET?

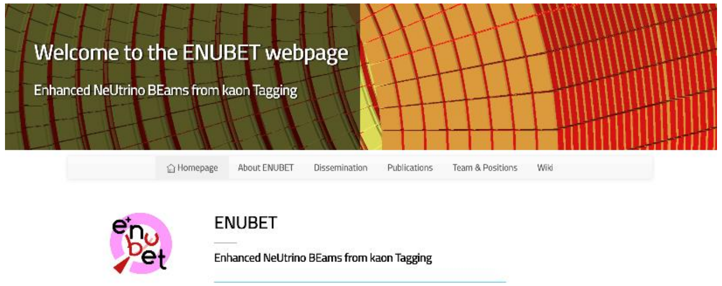
ENUBET is the project for the realization of the first monitored neutrino beam.

“Monitored neutrino beams are beams where diagnostic can directly measure the flux of neutrinos because the experimenters monitor the production of the lepton associated with the neutrino at the single-particle level. “
(Wikipedia)



- ENUBET: ERC Consolidator Grant, June 2016 – May 2021 (COVID: extended to end 2022). **PI: A. Longhin**;
  - Since April 2019: CERN Neutrino Platform Experiment – NP06/ENUBET – and part of Physics Beyond Colliders;
    - Collaboration: 65 physicists & 13 institutions; Spokespersons: A. Longhin, F. Terranova; Technical Coordinator: V. Mascagna;

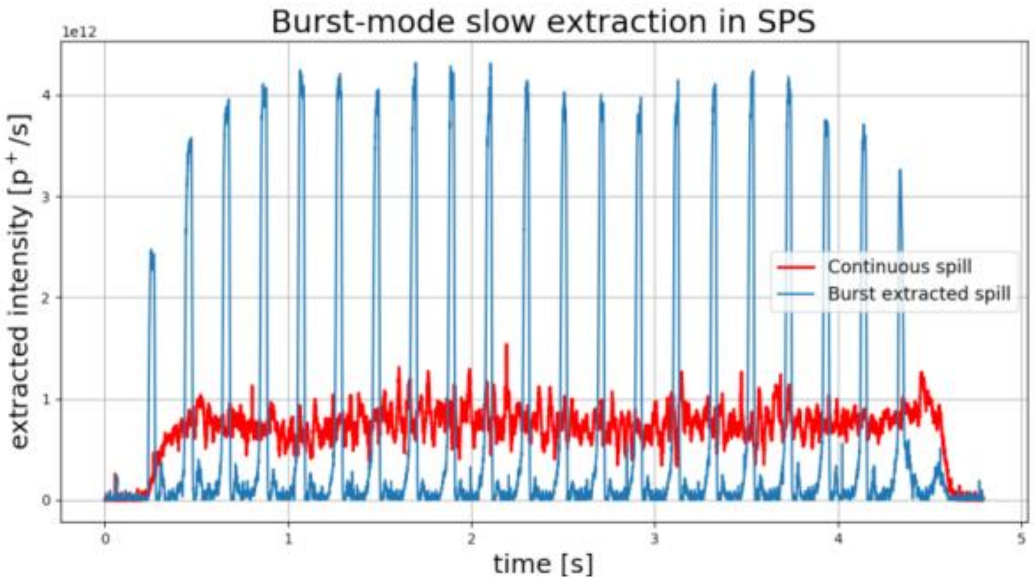
Visit our webpage for further info and material!
https://www.pd.infn.it/eng/enubet/



The 2020 breakthrough: a high-intensity horn-less neutrino beam

When we first proposed ENUBET, we were aiming at a beam where the leptons in the decay tunnel are produced at **slow rate** because we were afraid of pile-up and saturation of the instrumentation in the tunnel

Original design: a horn pulsed every 100 ms with a 10 ms pulse ("burst proton extraction")



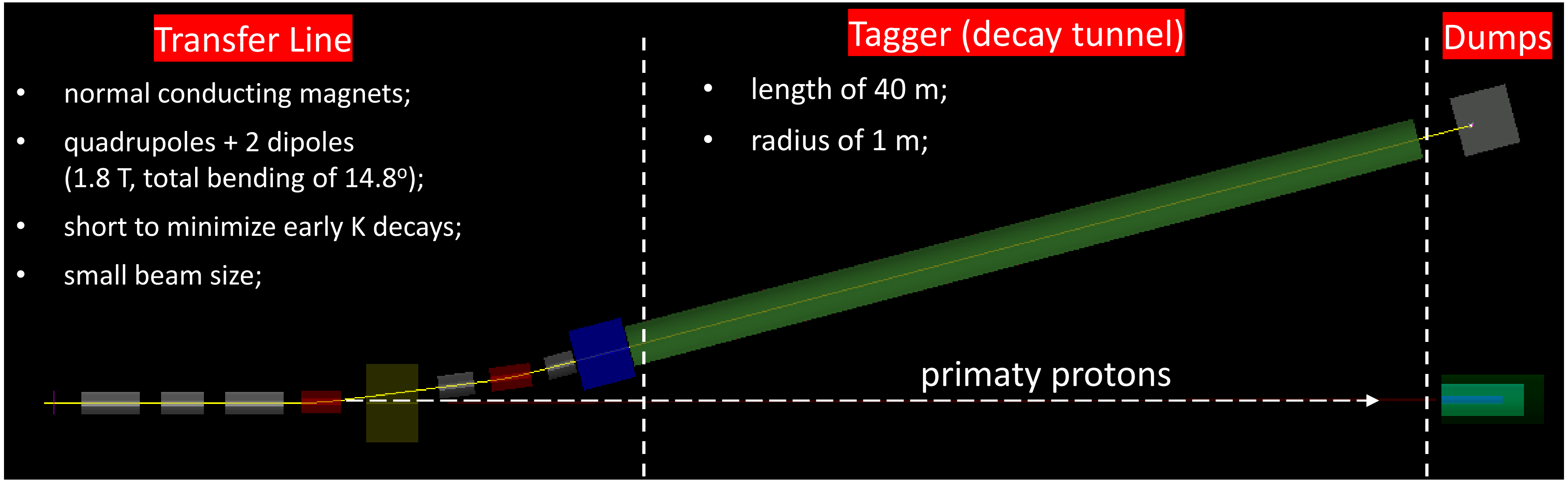
First demonstration of this proton extraction scheme in 2018 at CERN-SPS

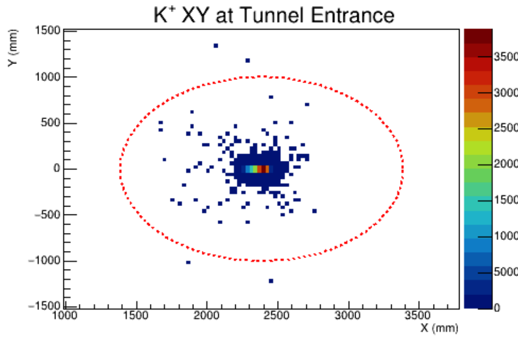
M. Pari, M. A Fraser et al, IPAC2019

2020 design ("static focusing system"): a neutrino beam without a horn where focusing at 8 GeV/c is accomplished by quadrupoles (like e.g. NuTeV but at much lower energy!)

The design was so successful that it achieved a flux that is just 2 times smaller than the corresponding horn-based design but protons are extracted in 2 seconds!! Rates reduced by more than one order of magnitude!

The ENUBET beamline (details in A. Branca ICHEP2022)





Rates @ Tunnel entrance for 400 GeV POT	
π^+ $[10^{-3}]$/POT	K^+ $[10^{-3}]$/POT
4.13	0.34

~1.5X w.r.t. previous results

Large bending angle of 14.8°:

- better collimated beam + reduced muons background + reduced ν_e from early decays;

Transfer Line:

- optics optimization w/ **TRANSPORT** (5% momentum bite centered @ 8.5 GeV) **G4Beamline** for particle transport and interactions;
- **FLUKA** for irradiation studies, **absorbers and rock** volumes included in simulation (not shown above);
- **optimized graphite target** 70 cm long & 3 cm radius (dedicated studies, scan geometry and different materials);
- **tungsten foil downstream target** to suppress positron background;
- tungsten alloy **absorber @ tagger entrance** to suppress backgrounds;

Dumps:

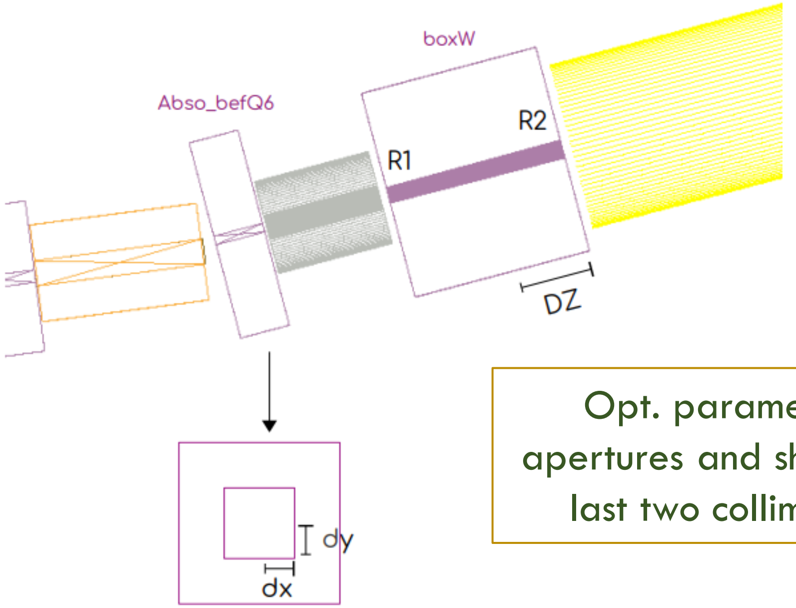
- **Proton dump**: three cylindrical layers (graphite core -> aluminum layer -> iron layer);
- **Hadron dump**: same structure of the proton dump -> allows to reduce backscattering flux in tunnel;

Full facility implemented in GEANT4:
- Controll over all paramaters;
- Access to the paricles histories;

assessment of the nu flux systematics

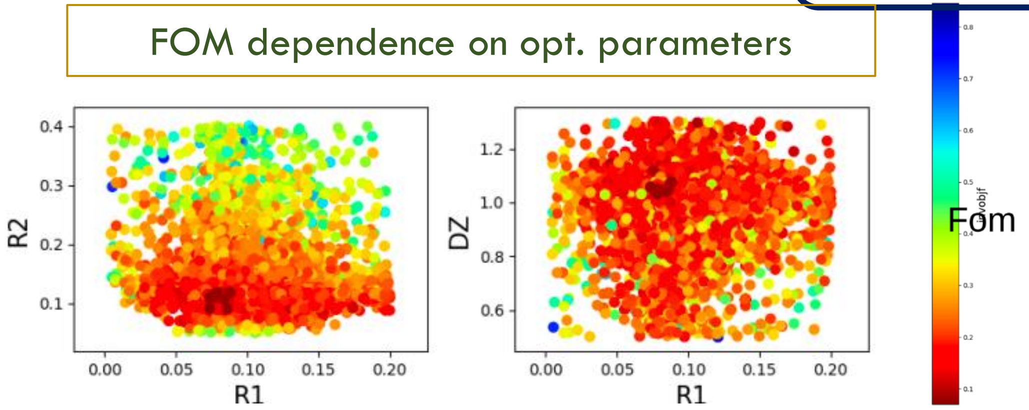
The ENUBET beamline: optimization studies

These are the ICHEP2022 results. Optimization completed in Oct 2022. Final results in Jan 2023



Opt. parameters: apertures and shapes of last two collimators

FOM dependence on opt. parameters



FOM = signal/background

Signal: π & K @ tagger enterance

Background: e^+ & π hitting tunnel walls

Rates @ Tunnel entrance for 400 GeV POT	π^+ $[10^{-3}]$/POT	K^+ $[10^{-3}]$/POT
Design	4.13	0.34
Optimized	5.27	0.44

Preliminary

Background hitting tunnel walls	$e^+[10^{-3}]/K^+$	$\pi^+[10^{-3}]/K^+$
Design	7	59
Optimized	2	35

Preliminary

An optimization campain is ongoing:

- **Goal**: further improvement of the π/K flux at tunnel entrance while keeping background level low;
- **Strategy**: scan parameters space of beamline to maximize FOM;
- **Tools**: full facility implemented in Geant4 **->** controll with external cards all parameters **->** systematic optimization with developed framework based on genetic algorithm;

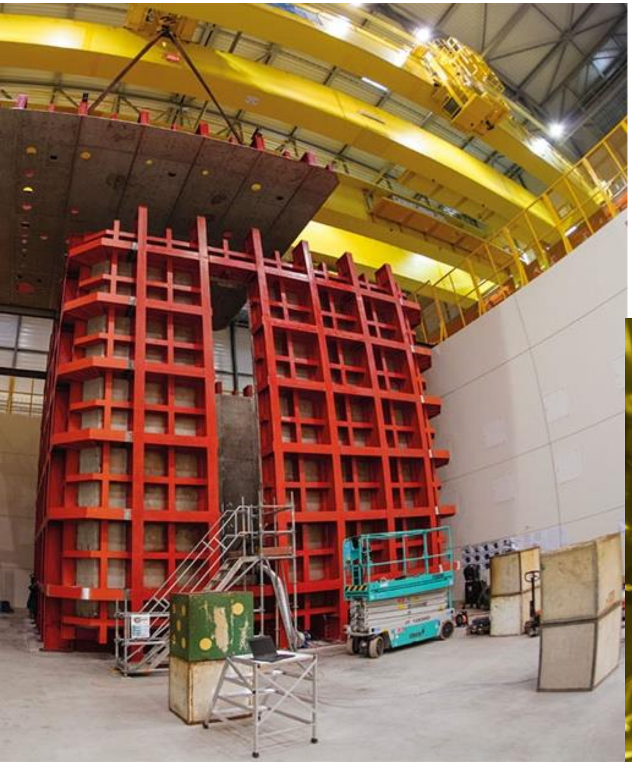
- About 28% gain in flux -> **2.4 years** to collect 10^4 ν_e^{CC};
- Reduced backgrounds, but similar to signal shapes -> next step: improve FOM definition (include sgn/bkg distributions);

Preliminary

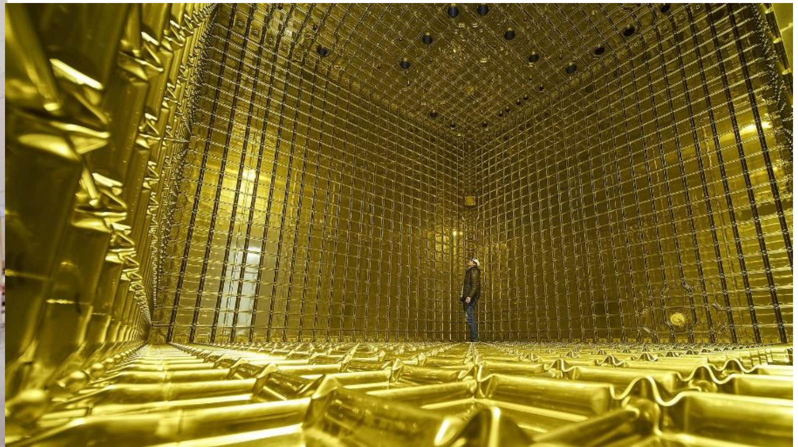
ν_e^{CC} energy distribution @ detector

A total ν_e^{CC} statistics of 10^4 events in ~2 years (aim of the optimization: 9 10^{19} pot if implemented at CERN SPS)

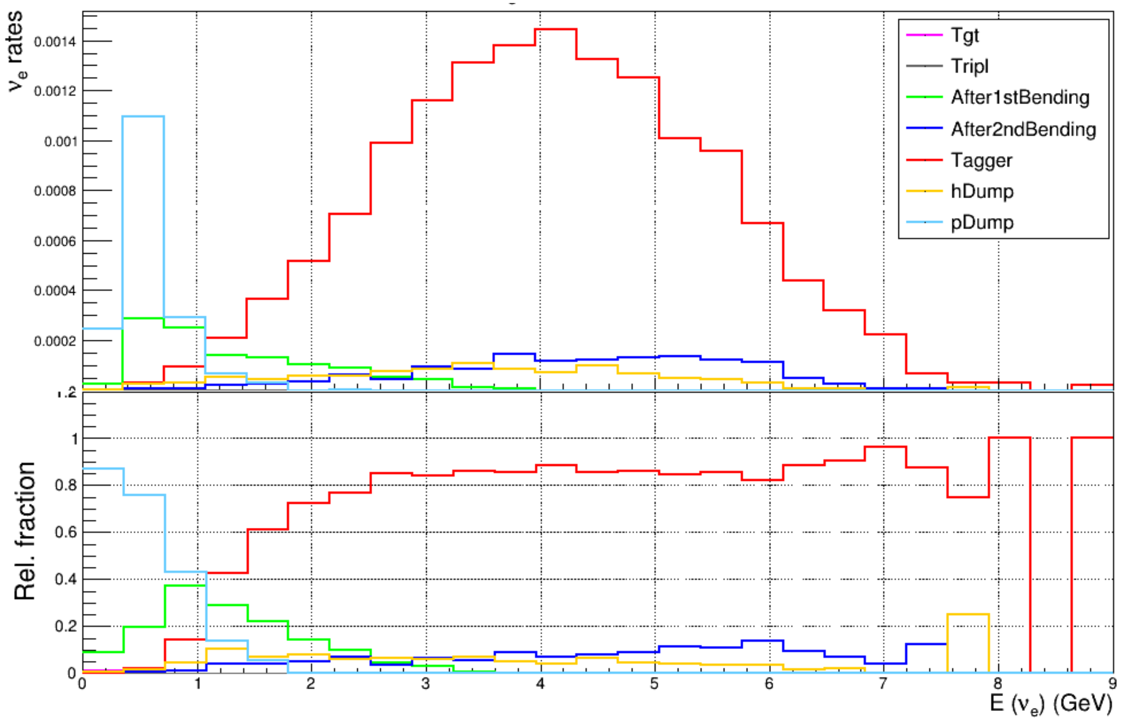
- @ SPS with $4.5 \cdot 10^{19}$ POT/year;
- 500 tonne detector @ 50 m from tunnel end;

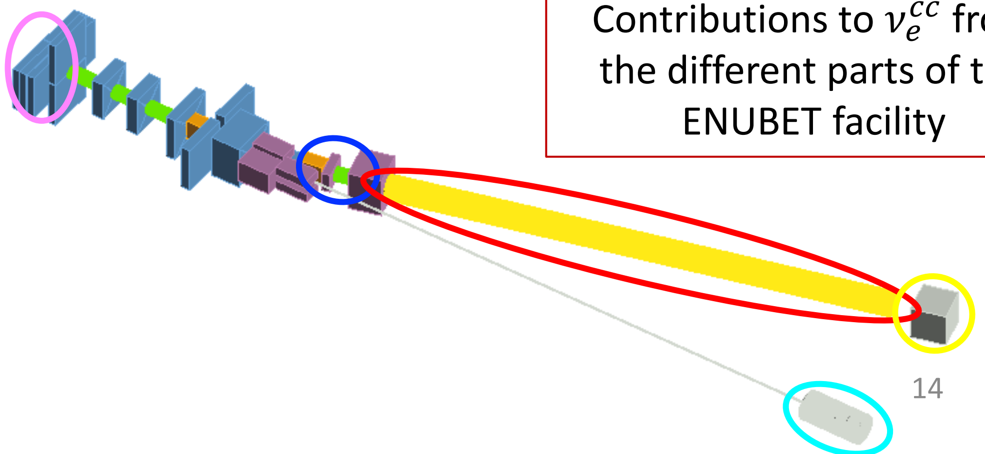


ProtoDUNE-SP (NP04)



ν_e CC spectra





Contributions to ν_e^{cc} from the different parts of the ENUBET facility

ν_μ^{CC} energy distribution @ detector

Narrow-band off-axis Technique

Narrow momentum beam O(5-10%)

(E_ν,R) are strongly correlated

E_ν = neutrino energy;

R = radial distance of interaction vertex from beam axis;

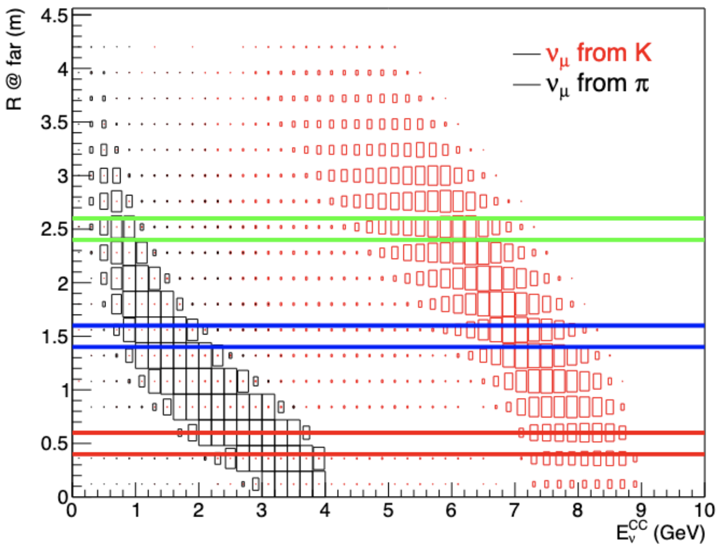
F. Acerbi et al., CERN-SPSC-2018-034

Precise determination of E_ν :
no need to rely on final state particles from ν_μ^{CC} interaction

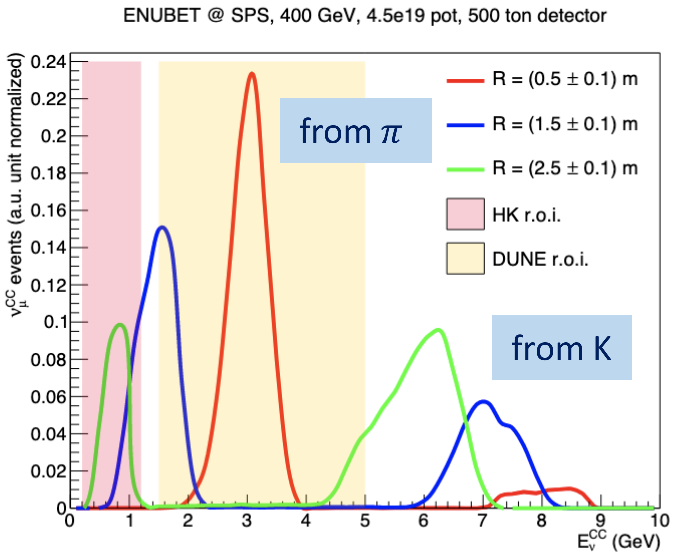
8-25% E_ν resolution from π in the DUNE energy range

30% E_ν resolution from π in HyperK energy range (DUNE optimized TL w/ 8.5 GeV beam):

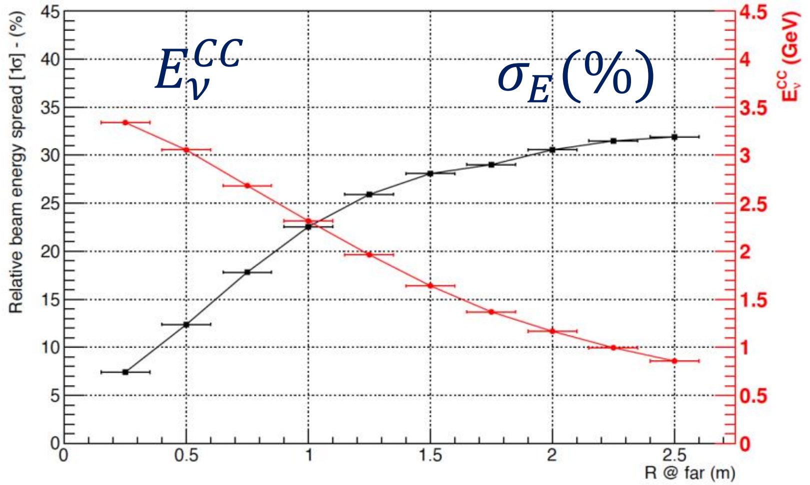
- ongoing R&D: Multi-Momentum Beamline (4.5, 6 and 8.5 GeV) => HyperK & DUNE optimized;



select slices in R windows



π/K populations well separated



from pion peaks at different R

Decay tunnel instrumentation

Shielding

- 30 cm of borated polyethylene;
- SiPMs installed on top -> factor 18 reduction in neutron fluence;

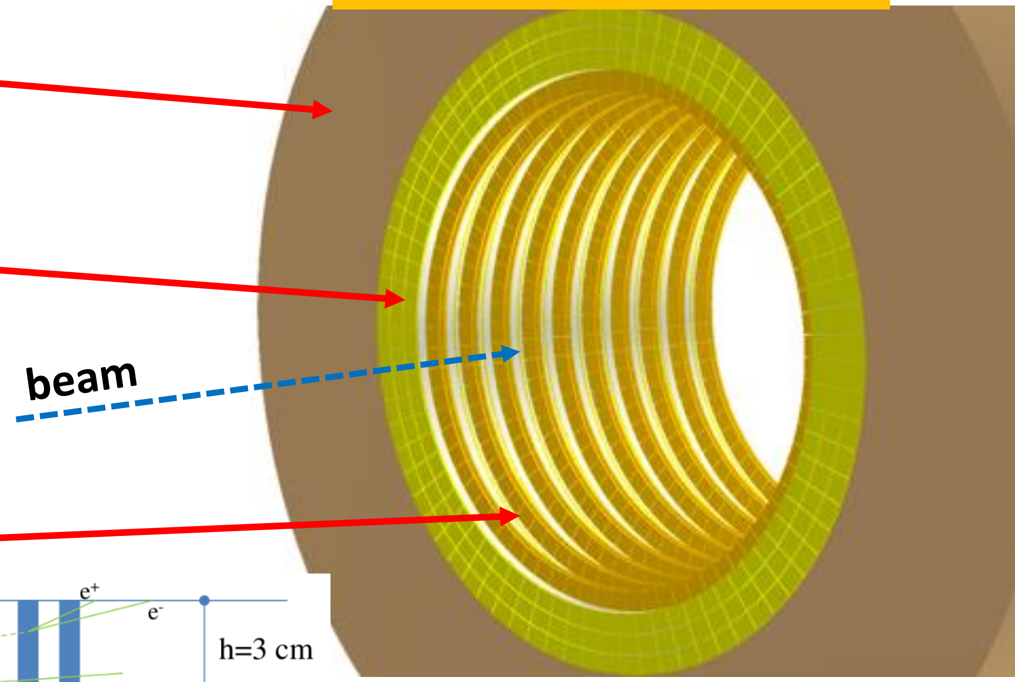
Calorimeter with $e/\pi/\mu$ separation capabilities:

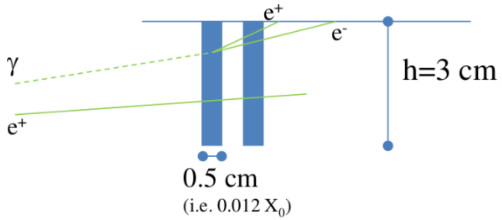
- sampling calorimeter: sandwich of plastic scintillators and iron absorbers;
- three radial layers of LCM / longitudinal segmentation;
- WLS-fibers/SiPMs for light collection/readout;

Photon-Veto allows π^0 rejection and timing:

- plastic scintillator tiles arranged in doublets forming inner rings;
- time resolution of ~ 400 ps;

Calorimeter layout



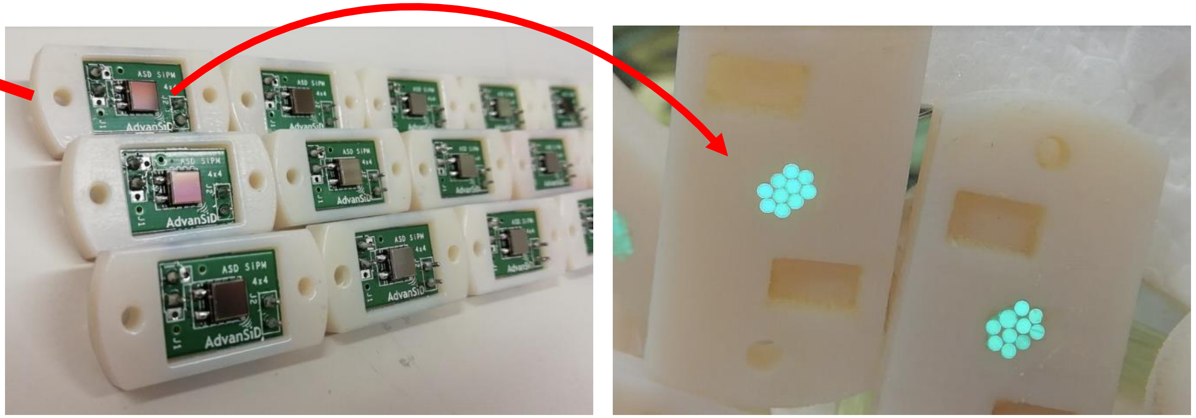


Exploit event topology for PID

Decay tunnel instrumentation prototype & tests

Prototype of sampling calorimeter built out of LCM with lateral WLS-fibers for light collection

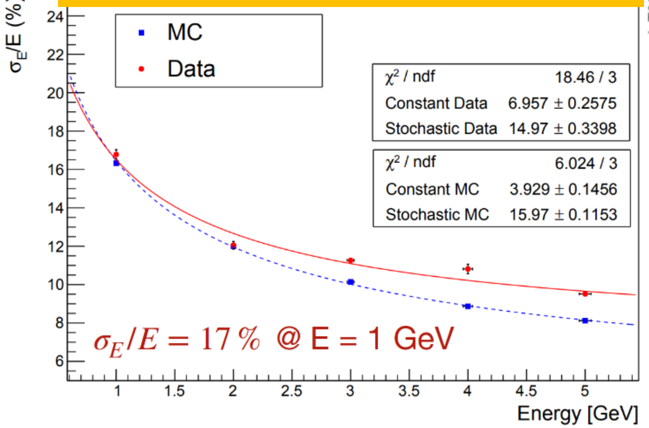
Large SiPM area (4x4 mm^2) for 10 WLS readout (1 LCM)



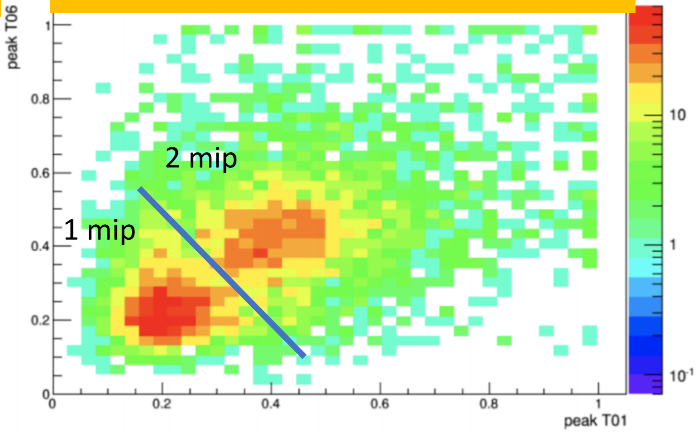
SiPMs installed outside of calorimeter, above shielding: avoid hadronic shower and reduce (factor 18) aging

Tested during 2018 test-beams runs @ CERN TS-P9

Electron energy resolution



1mip/2mip separation



Status of calorimeter:

- ✓ longitudinally segmented calorimeter prototype successfully tested;
- ✓ photon veto successfully tested;
- ➢ custom digitizers: in progress;

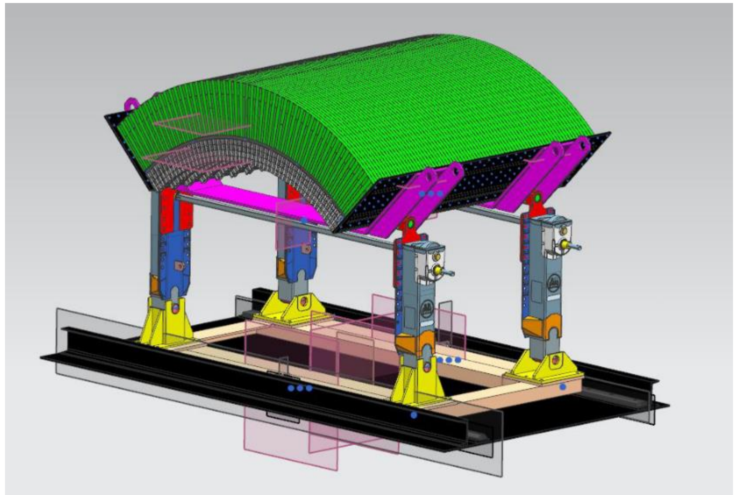
Choise of technology: finalized and cost-effective!

F. Acerbi et al, JINST (2020), 15(8), P08001

The ENUBET demonstrator

Construction @ LNL-INFN Labs

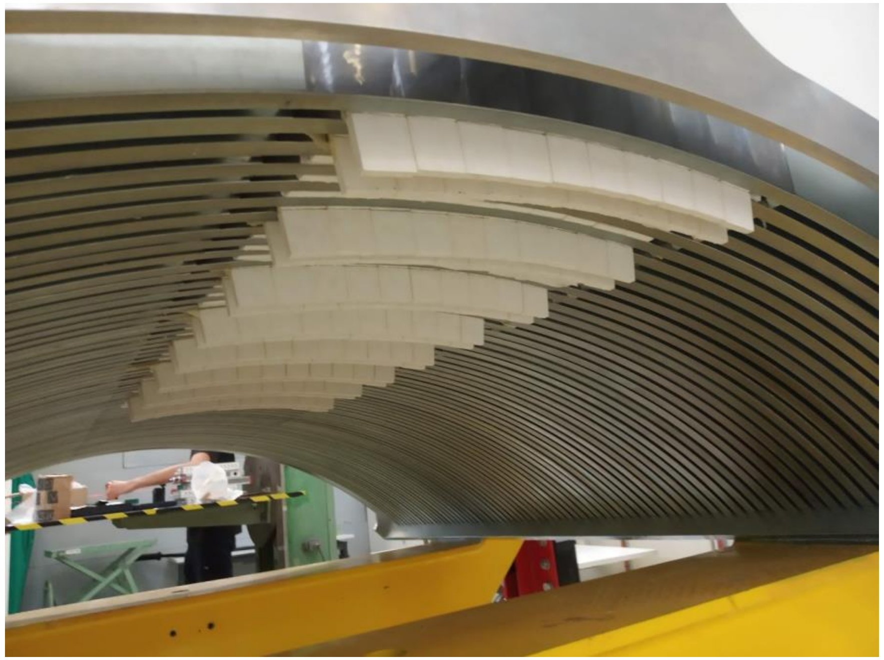
Iron arcs and borated polyethylen shielding

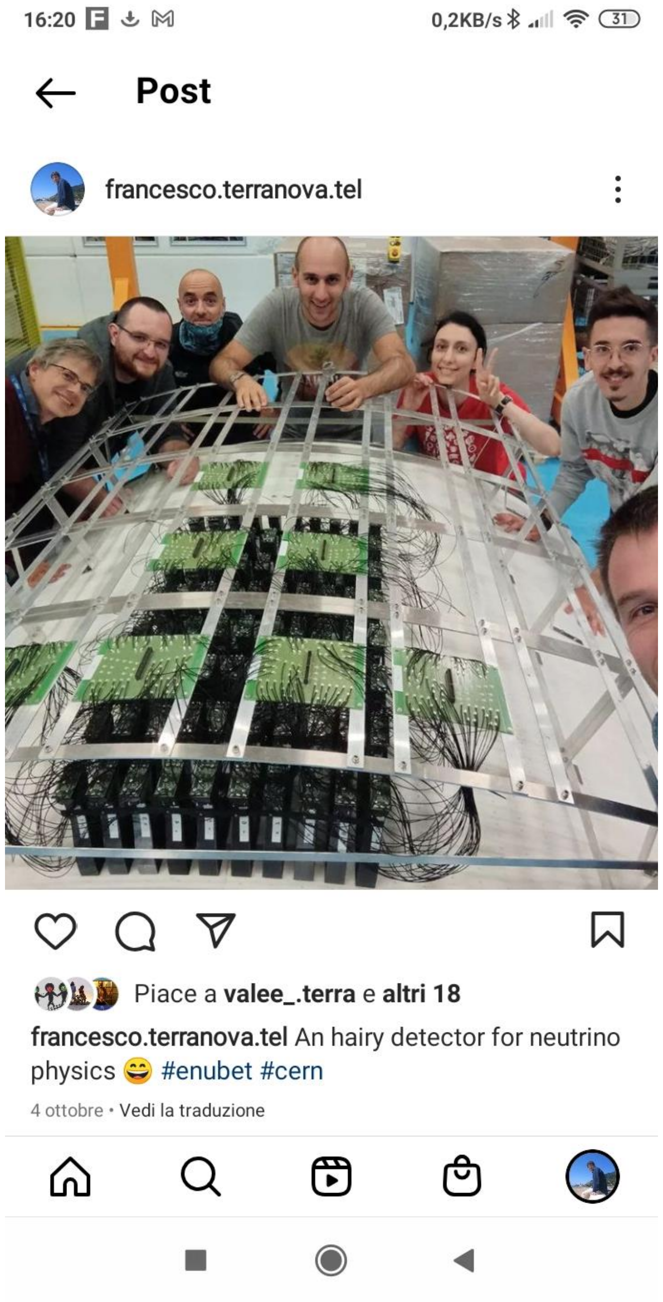


Lifting test of demonstrator

Fiber concentrator (boundling/routing to SiPMs)

The ENUBET demonstrator: at CERN PS-EA in Oct 2022!





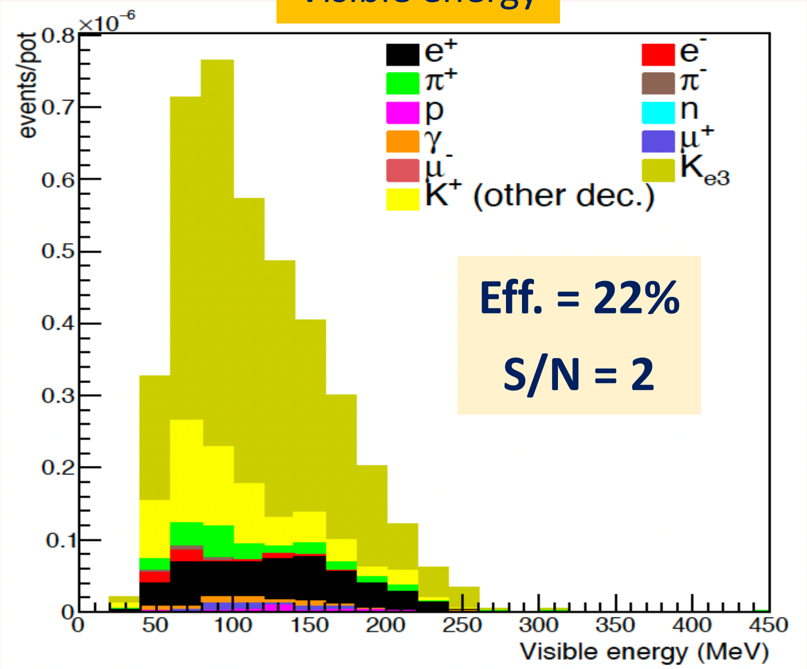
Lepton reconstruction and identification performance

Full GEANT4 simulation of the detector: validated by prototype tests at CERN in 2016-2018; hit-level detector response; pile-up effects included (waveform treatment in progress); event building and PID algorithms (2016-2020);

- Large angle positrons and muons from kaon decays reconstructed searching for patterns in energy depositions in tagger;
- Signal identification done using a Neural Network trained on a set of discriminating variables;

K_{e3} positrons -> constrain ν_e

Visible energy

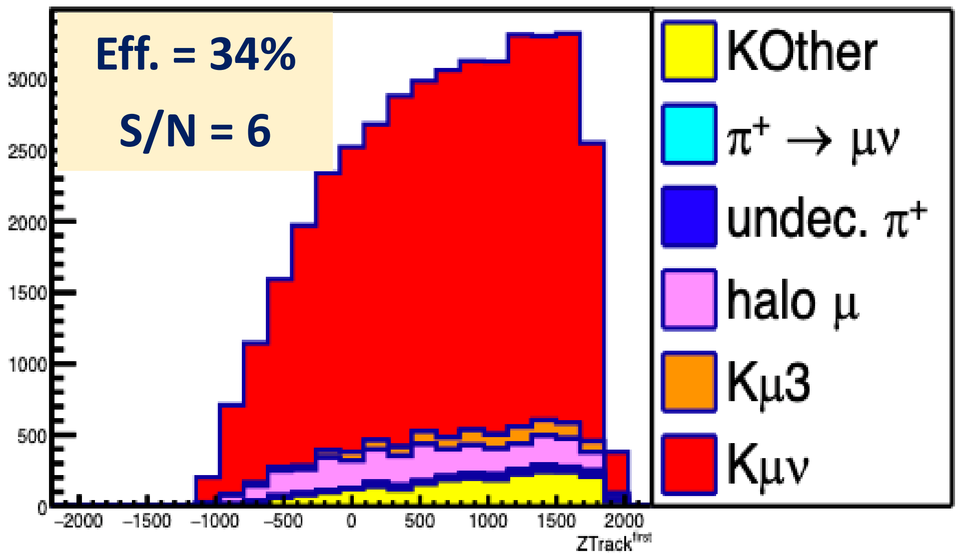


Efficiency ~half geometrical

K_{e3} BR $\sim 5\%$ and K make $\sim 5-10\%$ of beam composition

$K_{\mu 2}$ muons -> constrain ν_μ

Tagger impact point



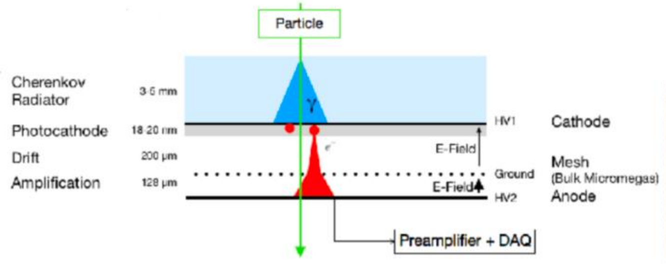
Efficiency ~half geometrical

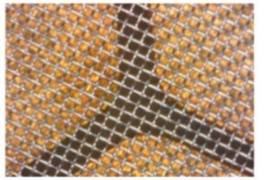
F. Pupilli et al., PoS NEUTEL2017 (2018) 078

Forward lepton reconstruction ($\pi \rightarrow \mu\ \nu_\mu$)

$\pi_{\mu 2}$ muon reconstruction to constrain low-energy ν_μ

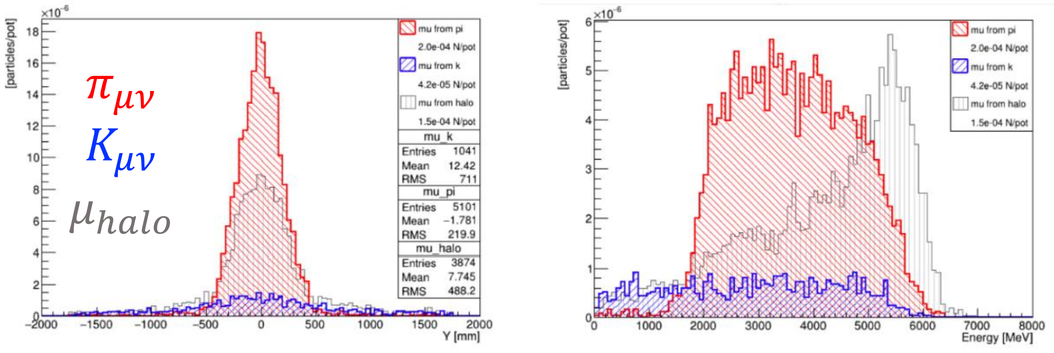
✓ **Low angle muons**: out of tagger acceptance, need muon stations after hadron dump

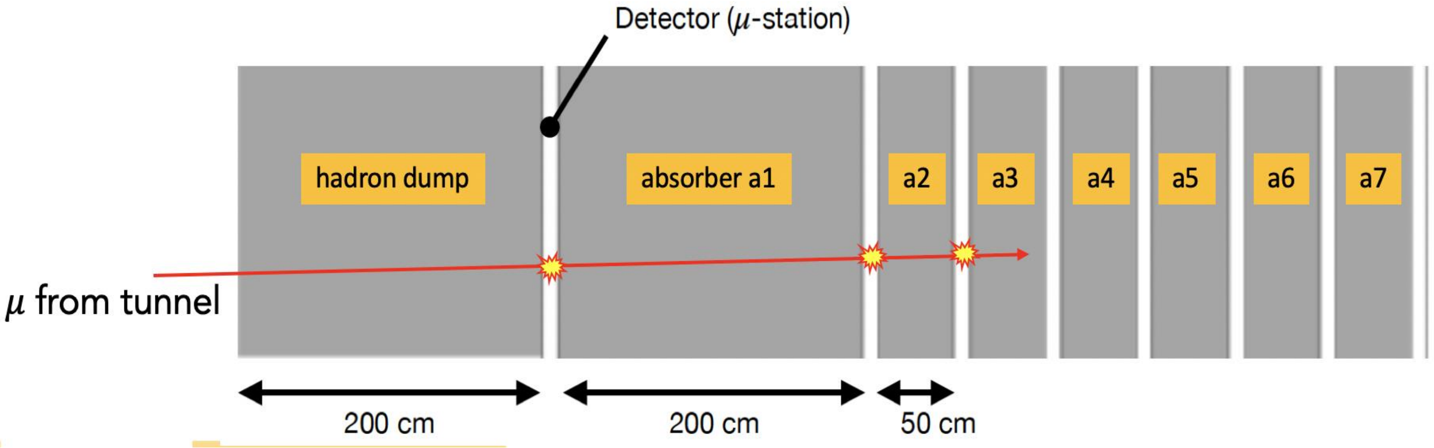


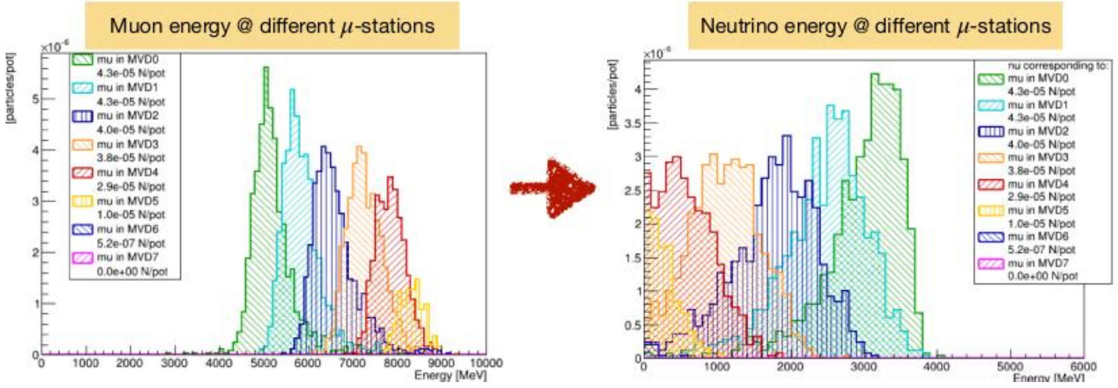


Possible candidates: fast Micromega detectors with Cherenkov radiators (PIMENT)

Exploit differences in distributions to disentangle components







Hottest detector (upstream station): cope with ~2 MHz/cm^2 muon rate and ~10^{12} 1 MeV-n$_{eq}$/cm^2

Exploit:

- ❖ correlation between number of traversed stations (muon energy from range-out) and neutrino energy;
- ❖ difference in distribution to disentangle signal from halo-muons;

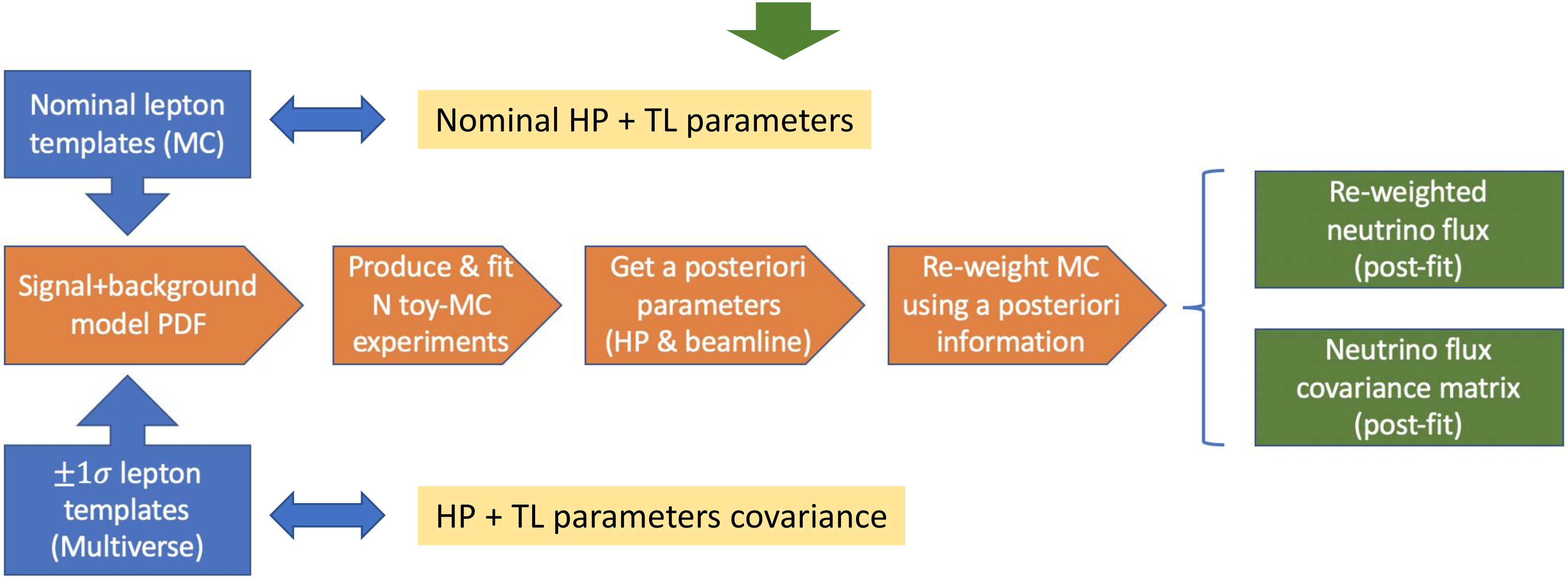
Detector technology: constrained by muon and neutron rates;

Systematics: punch through, non uniformity, efficiency, halo-μ;

ν-Flux: assessment of systematics

Monitored ν flux from narrow-band beam: measure rate of leptons ⟺ monitor ν flux

- build a Signal + Background model to fit lepton observables;
- include hadro-production (HP) & transfer line (TL) systematics as nuisances;

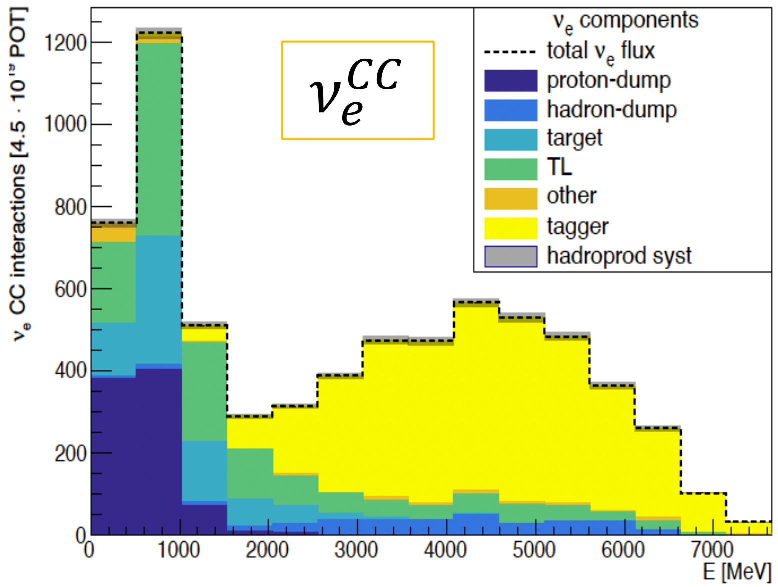


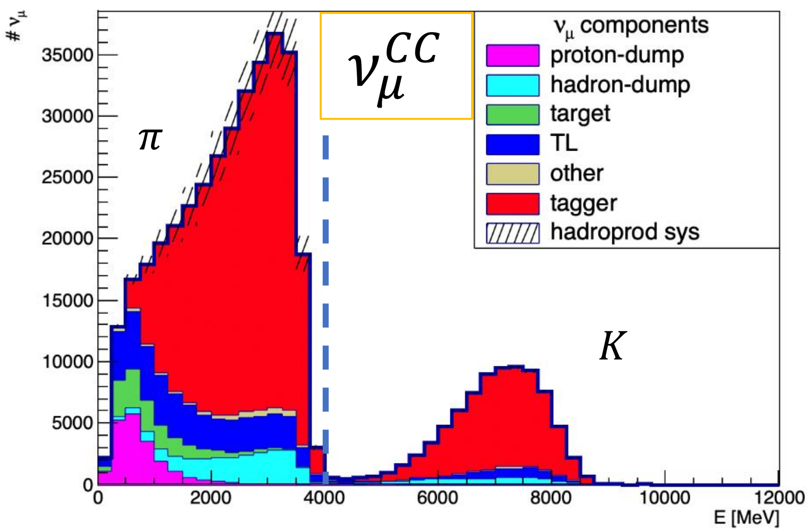
Used hadro-production data from NA56/SPY experiment to:

- Reweight MC lepton templates and get their nominal distribution;
- Compute lepton templates variations using multi-universe method;

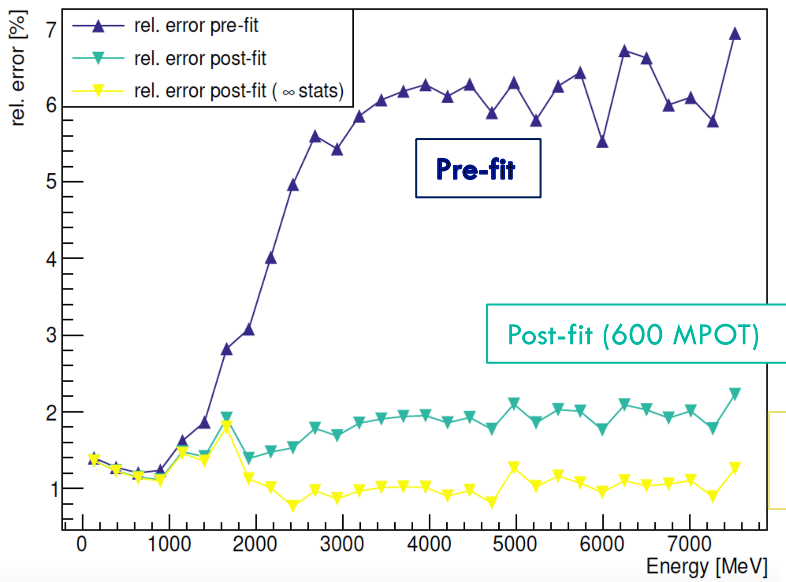
ν-Flux: impact of hadro-production systematics

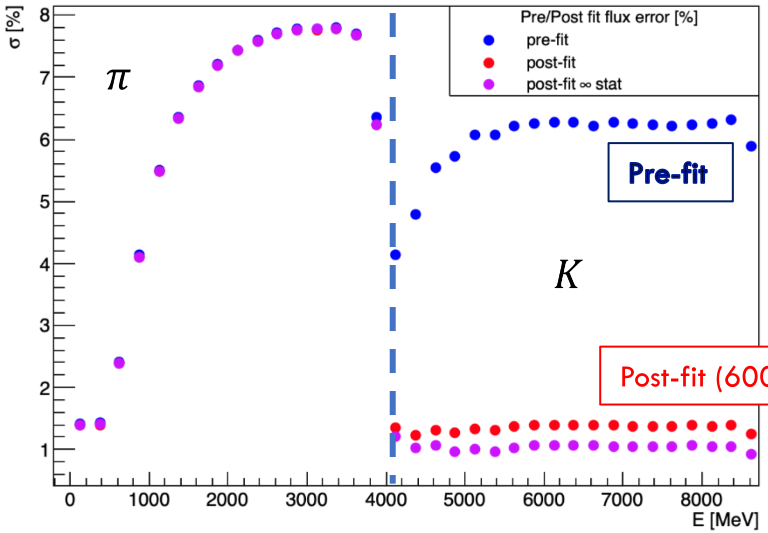
Neutrino interaction rates @ detector





Pre & Post fit relative errors on rates





Total rates in 1 year of data taking

- @ SPS with $4.5 \cdot 10^{19}$ POT/year;
- 500 ton detector @ 50 m from tunnel end;

NEW – Mar 2022 !

Before constraint: 6% systematics due to hadro-production uncertainties;
After constraint: 1% systematics from fit to lepton rates measured by tagger;

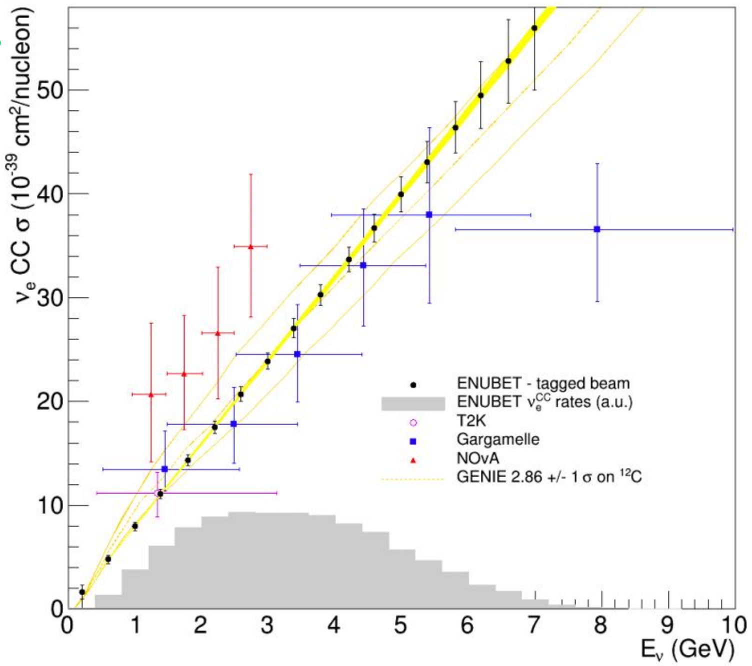
Achieved ENUBET goal of 1% systematics from monitoring lepton rates

Monitored neutrino beams are viable candidates!

- Measure the neutrino flux of a xsect-dedicated short baseline beam with a precision <1% in in ν_e and ν_μ
  - **OK**. ENUBET has achieved a precision of 1% considering the leading systematics and only positron monitoring (ICHEP2022). We will publish the final results including the muon constraints and the subdominant contributions in 2023
  - **Room for improvement**: reduce the need of protons-on-target to ease implementation at CERN. Enhance statistics in the region of interest for HyperK

- Measure the energy of the neutrino without relying on the final state to get rid of all biases coming from nuclear reinteractions
- **OK**. Using the fact that the ENUBET beam is narrow band we achieve an event-to-event resolution of 8% at 3 GeV and 25% at 1 GeV (“NBOA” technique)
- **Room for improvement**: a direct muon energy measurement can improve substantially this precision, especially at low E (tracking at the last dipole) [Nutech, NuTAG, PIMENT, Pine]
- Use the same target ad DUNE and HyperK + low Z target (existing or new experiments)
- **YES**. All results above work with a 400 ton detector. ProtoDUNE-SP at CERN is an asset **but** a full site-dependent (SPS@CERN) study is not available yet.

ENUBET impact on σ_{ν_e}



Toward a SBL neutrino beam at CERN

A successful R&D is not enough to propose a short baseline neutrino beam at CERN in 2029 (Run 4 of LHC, in parallel with the run of DUNE and HyperK). We need:

- To create **consensus** in the neutrino community. Detail the physics case and the detector requirements
- To be **realistic** as regards the site implementation. We need 5-9 10^{19} proton-on-target in 2-5 years and a location that can fit a suite of detectors, possibly including ProtoDUNE-SP and ProtoDUNE-DP (now called "ProtoDUNE-VD").
- To **be optimistic** ☺ The physics case is strong and already attracted the interest of NUSTEC, DUNE, and HyperKamiokande. We need to transform this generic interest in a real proposal by 2025

Framework:

- We are carrying on the beam optimization (pot reduction, energy measurement) and site-dependent study in the framework of **Physics Beyond Collider** at CERN
- We are detailing the physics case with **nuSTORM** because many items are in common
- The ENUBET physicists are deeply involved in **DUNE and HyperK** and they are aware of the needs of these experiments and complementarity with the Near Detector measurements

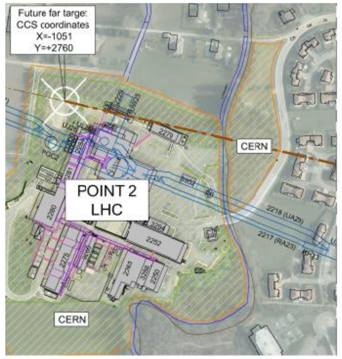
The CERN facilities

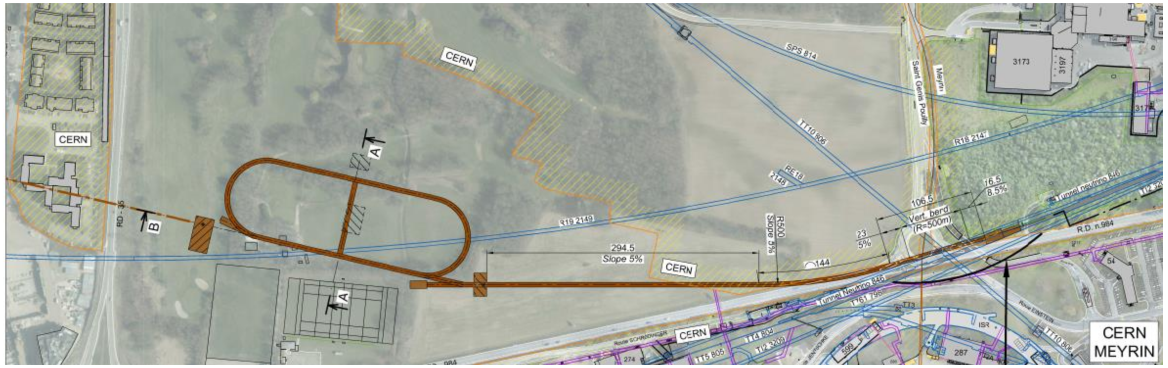
A short baseline neutrino beam at the SPS was studied in detail in 2010-12 for sterile neutrino searches (ICARUS-NESSIE Collaboration, 100 GeV protons from SPS – M. Antonello et al., CERN-SPSC-2012-010).

Figure 1. The new SPS North Area neutrino beam layout. Main parameters are: primary beam : 100 GeV; fast extracted from SPS; target station next to TCC2, ~11m underground; decay pipe: 100m, 3 m diameter; beam dump : 15m of Fe with graphite core, followed by muon stations; neutrino beam angle: pointing upwards; at -3m in the far detector ~5mrad slope. From I. Efthymiopoulos / CERN.

This are host now the EHN1 extension and is served by a dedicated (low intensity!) charged particle beamline: a tertiary extension branch of the H4 beam line in the CERN North Area (H4-VLE).

A design study compatible with ENUBET but aimed at nuSTORM was carried out in 2019 for a possible implementation of nuSTORM at CERN (C.C. Ahida et al., CERN-PBC-REPORT-2019-003)





It exploits an existing transfer line in the Meyrin site (TT60) and requires a dedicated detector site.

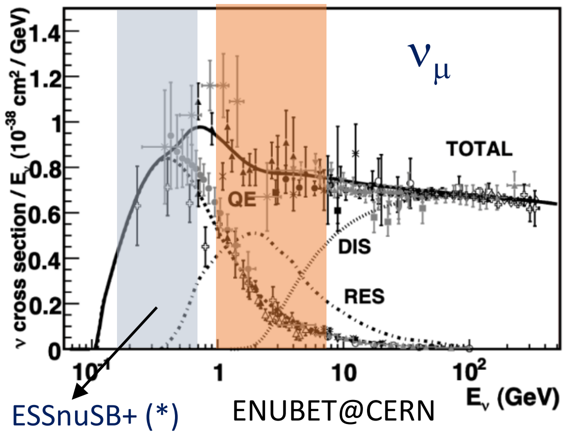
The CERN (site dependent) study

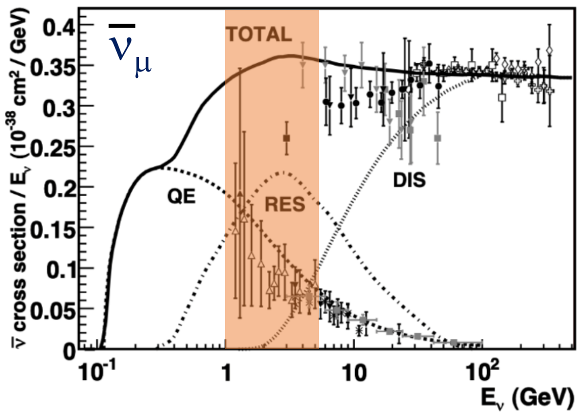
Three options are currently under consideration:

- The cheapest: a dedicated neutrino beamline extracted from the North area and pointing toward ProtoDUNE
  - Maximum use of existing facilities
  - Slow extraction easily implemented
  - Strong interference with other experiments
  - Potential radiation issues
- The cleanest: a dedicated extraction line near the North area pointing to ProtoDUNE
  - No interference with experiments and existing facilities
  - Minor radiation issues
  - Slow extraction
  - Higher cost
- The nuSTORM-like extraction line
  - Relatively cheap
  - Incompatible with ProtoDUNE in their current position
  - Potential issues with the slow extraction

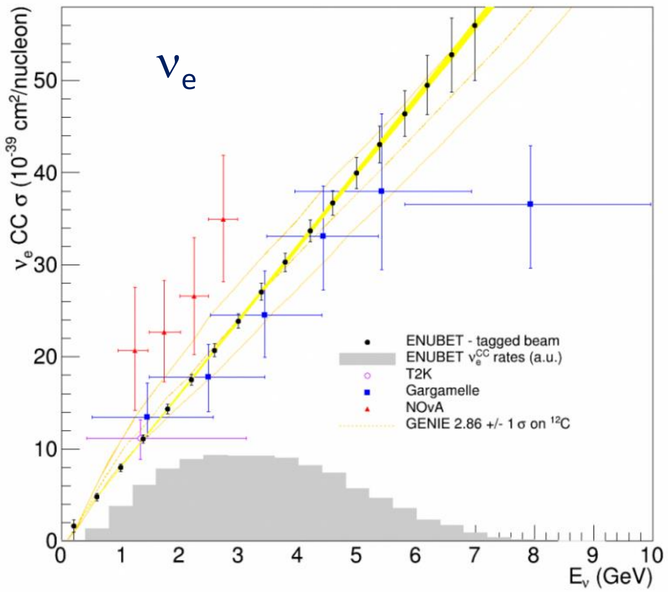
Physics case: SM physics

Inclusive neutrino cross section: solid results already available

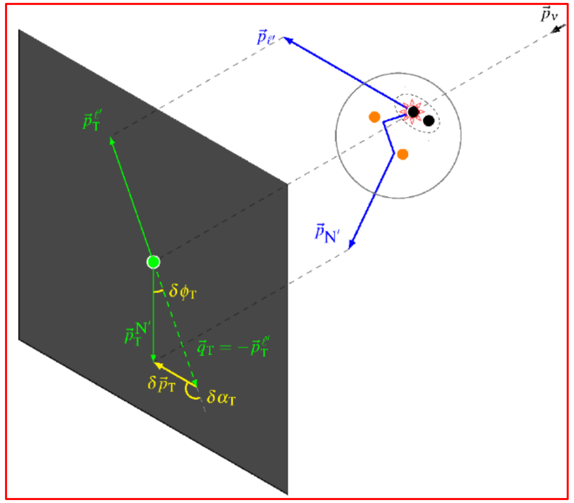




(*) monitored neutrino beam @ESS Design studied approved by EU (lead CNRS) in July 2022



Differential cross sections:

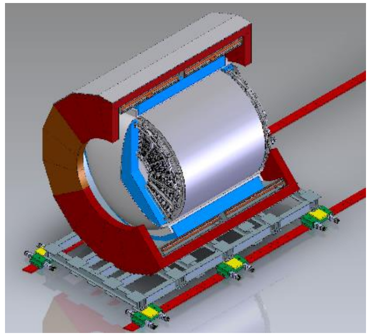


Exploit the knowledge of the neutrino energy without relying on final states: ENUBET NBOA + transverse kinematic embalance (*)

(*) X.G. Lu et al. PRC 94 (2016) 105503

Low Z and low-density targets:

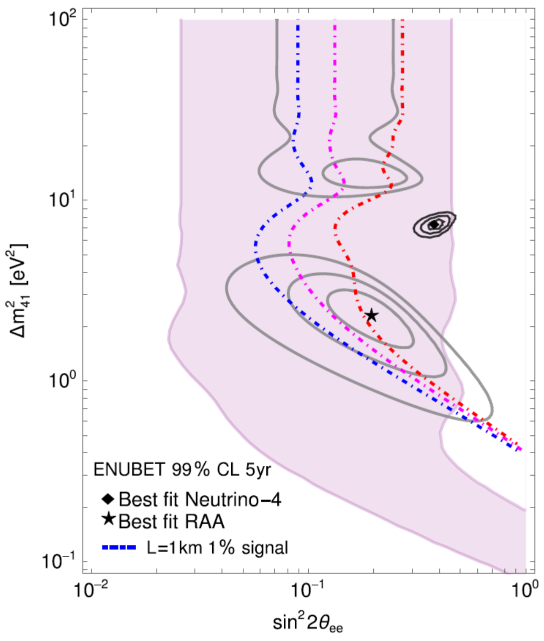
M. Hartz et al., CERN-SPSC-2020-005; SPSC-P-365
A. Abed Abud, arXiv:2203.06281
L. Alvarez-Rouso et al., arXiv:2203.11298
H. Duyang et al., PLB 795 (2019) 424

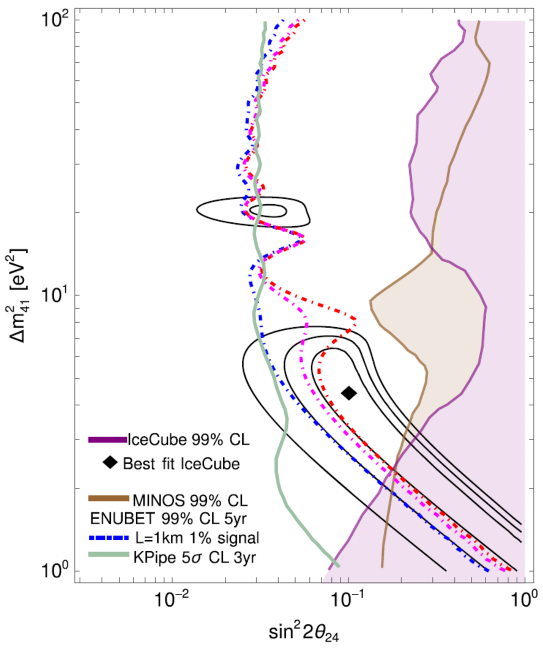


Physics case: BSM physics and parasitic measurements

Sterile neutrinos: some results already available
L.A. Delgadillo, P. Huber, PRD 103 (2021) 035018

Non-Standard interactions: to be investigated





Instrumented proton and hadron dump:

P. S. Bhupal Dev, Doojin Kim, K. Sinha, Yongchao Zhang, Phys. Rev. D 104, 035037 [**ALP**]

J. Spitz, Phys. Rev. D 89 (2014) 073007 [**KDAR**]

Work ongoing for studies of Dark Sector and non-standard neutrino interactions to assess potential of SBL versus Near detectors:

Pro: energy control of the incoming flux. Outstanding precision on the flux and flavor composition

Cons: Limited statistics

Conclusions

- Monitored neutrino beams are no more an "interesting idea": the proof-of-concept is nearly complete and NP06/ENUBET has proven it both by simulations and a full experimental validation
- A monitored neutrino beam has all features needed for a new generation of cross section experiments
- The final ENUBET results (baseline beamline, multi-momentum beamline, systematic assessment, and performance of the demonstrator) will appear in journals (4 papers) in 2023.
- We have started the process of addressing the real implementation at CERN and aim at a proposal in 2024-2025 to be in data taking for LHC Run IV (2029)
- This is a major effort that requires:
  - Careful assessment of physics performance
  - Assets and limitations for the use of ProtoDUNE (e.g. cosmic rejection in a slow extraction, kinematic reconstruction of final states, etc.)
  - Optimal location at CERN to exploit the SPS slow extraction

We look forward to your suggestions for a design that fulfill the needs of the neutrino and nuclear physicists to have these experiment up and running in parallel with DUNE and HyperK